Ultra-light Axion Dark Matter and CMB B-mode Polarization

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A HIGH-ENERGY NEUTRINO SIGNATURE FROM SUPERSYMMETRIC RELICS

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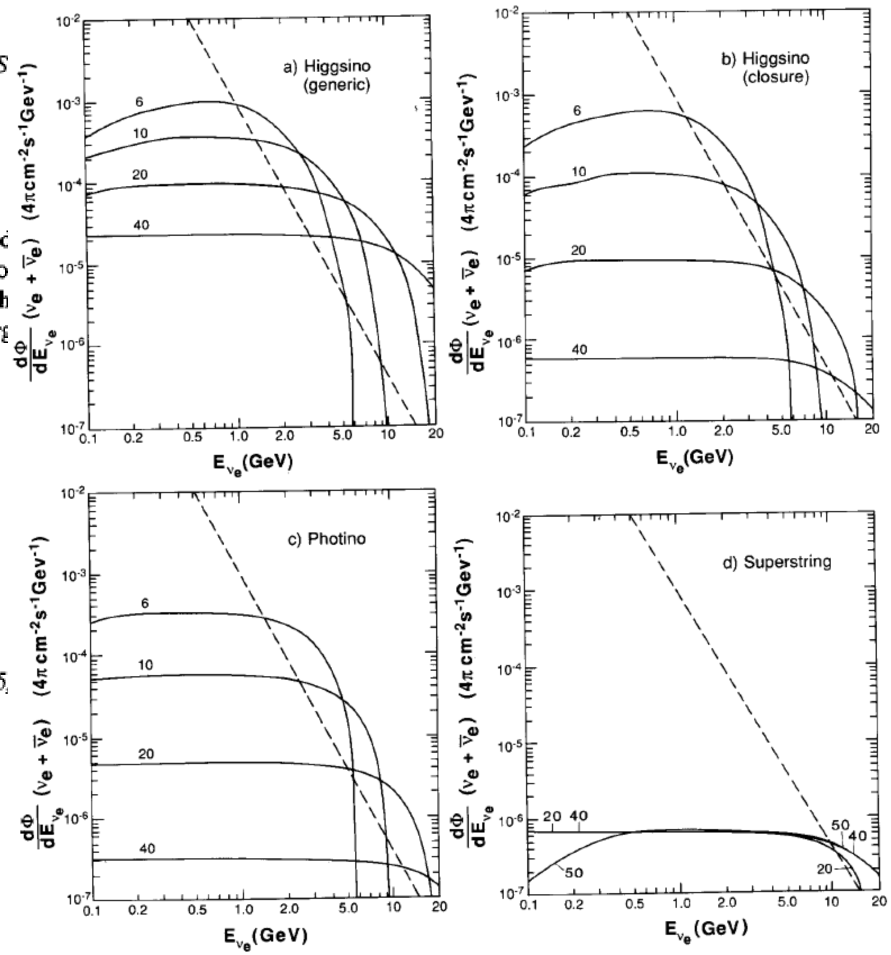
Received 21 July 1986

We compute the energy spectrum of high-energy (0.1–10 GeV) neutrinos proc metric (SUSY) cold dark matter trapped in the sun. We compare this spectrum to and find that in the direction of the sun the solar flux of neutrinos can exceed th energies $E_\nu \gtrsim 1$ GeV, and are as much as a factor ~30 above background for energ natures for standard SUSY relics as well as for superstring relics.

1987A Kamiokande, IMB,..



DARK MATTER INDUCED NEUTRINOS FROM THE SUN: THEORY VERSUS EXPERIMENT

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and

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Received 30 December 1986

We analyse the restrictions from experimental data on high-energy neutrinos from the sun due to the annihilation of cold dark matter. We pay particular attention to uncertainties in the neutrino-, particle- and astro-physics. We conclude that photinos and higgsinos cannot be ruled out by the present IMB data. However, it appears safe to say that muon sneutrinos are not a viable candidate.

Keith’s small fuel-economy car in mid 80s

Keiths’ favorite food

Dynamical Dark Energy and Its Coupling to Matter

Kin-Wang Ng

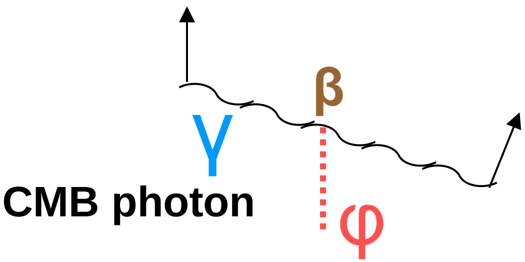
Academia Sinica & LeCosPA, Taiwan & KIPAC, SLAC

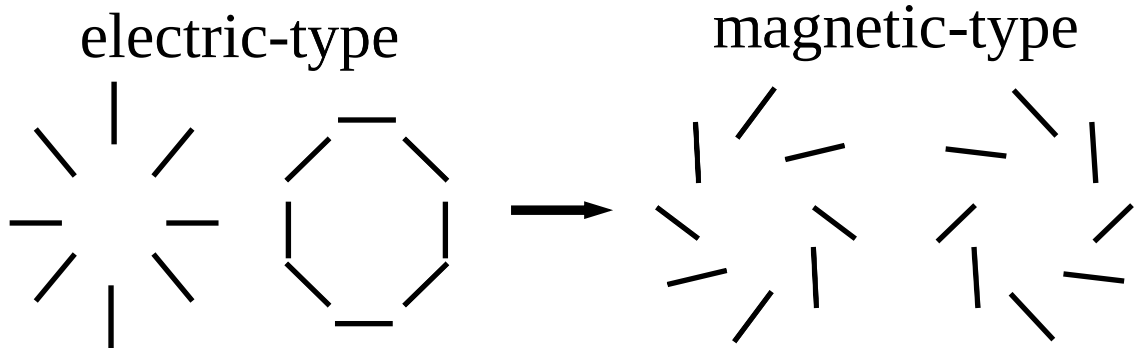
UM Cosmology Lunch Seminar Sep 28, 2009

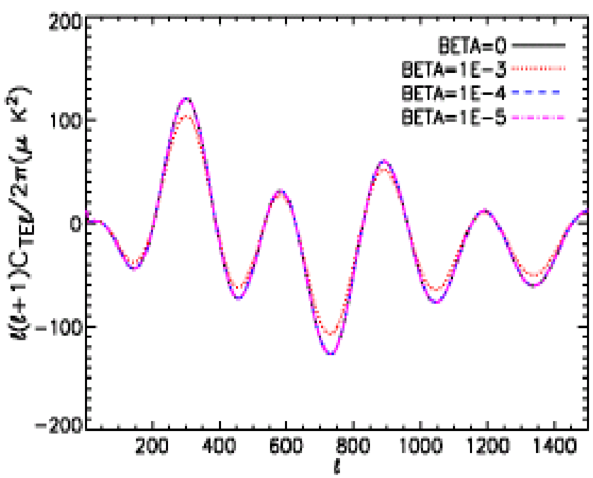
Collaborators: **Da-Shin Lee (NDHU)**
Wolung Lee (NTNU)
Guo-Chin Liu (TKU)
Seokcheon Lee(ASIoP)
Chao-Lin Kuo (Stanford)

DE mean field induced vacuum birefringence – cosmic rotation of CMB polarization

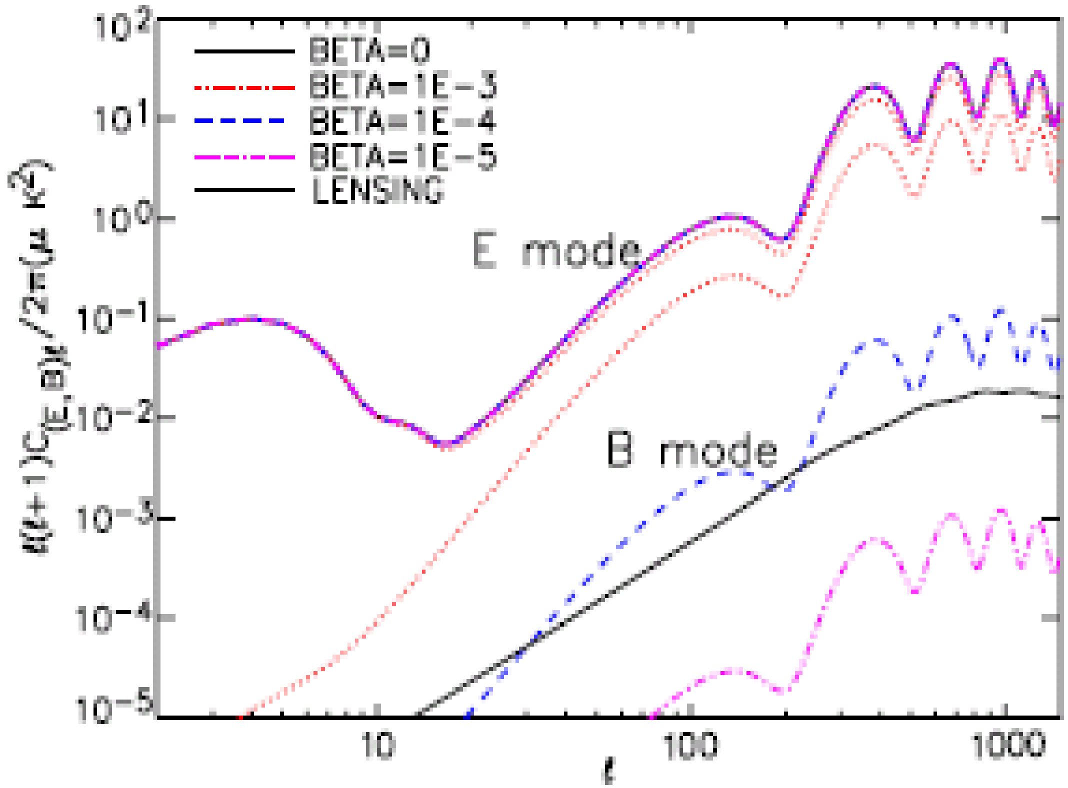
Liu,Lee,Ng 06



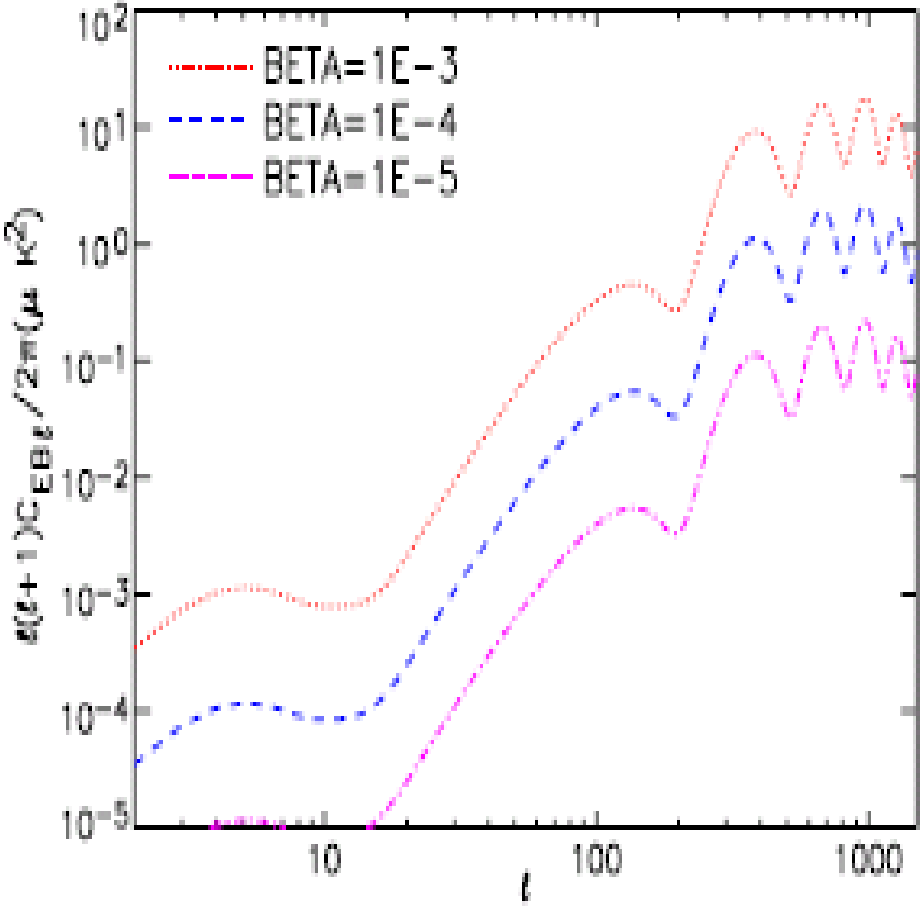


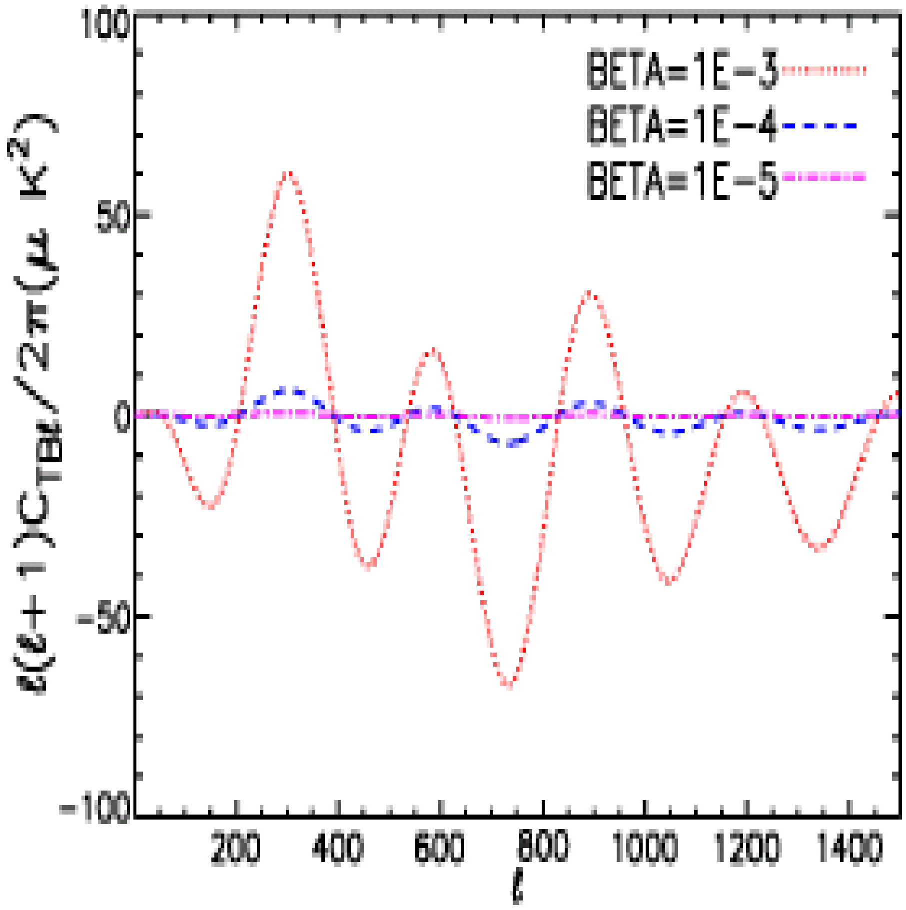


TE spectrum



Parity violating EB,TB cross power spectra – cosmic parity violation





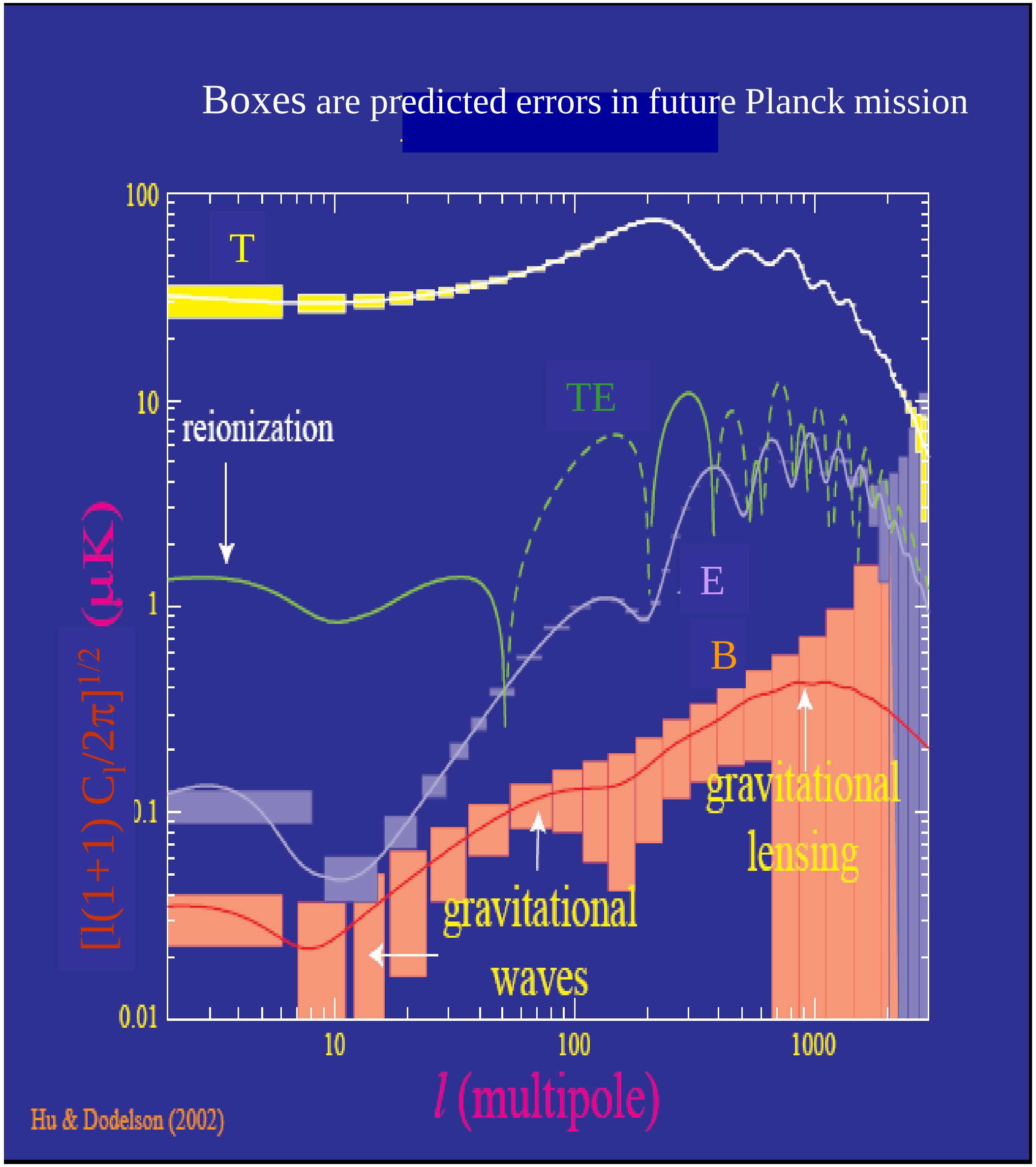
Axion-like DE and CDM

(too many references to list)

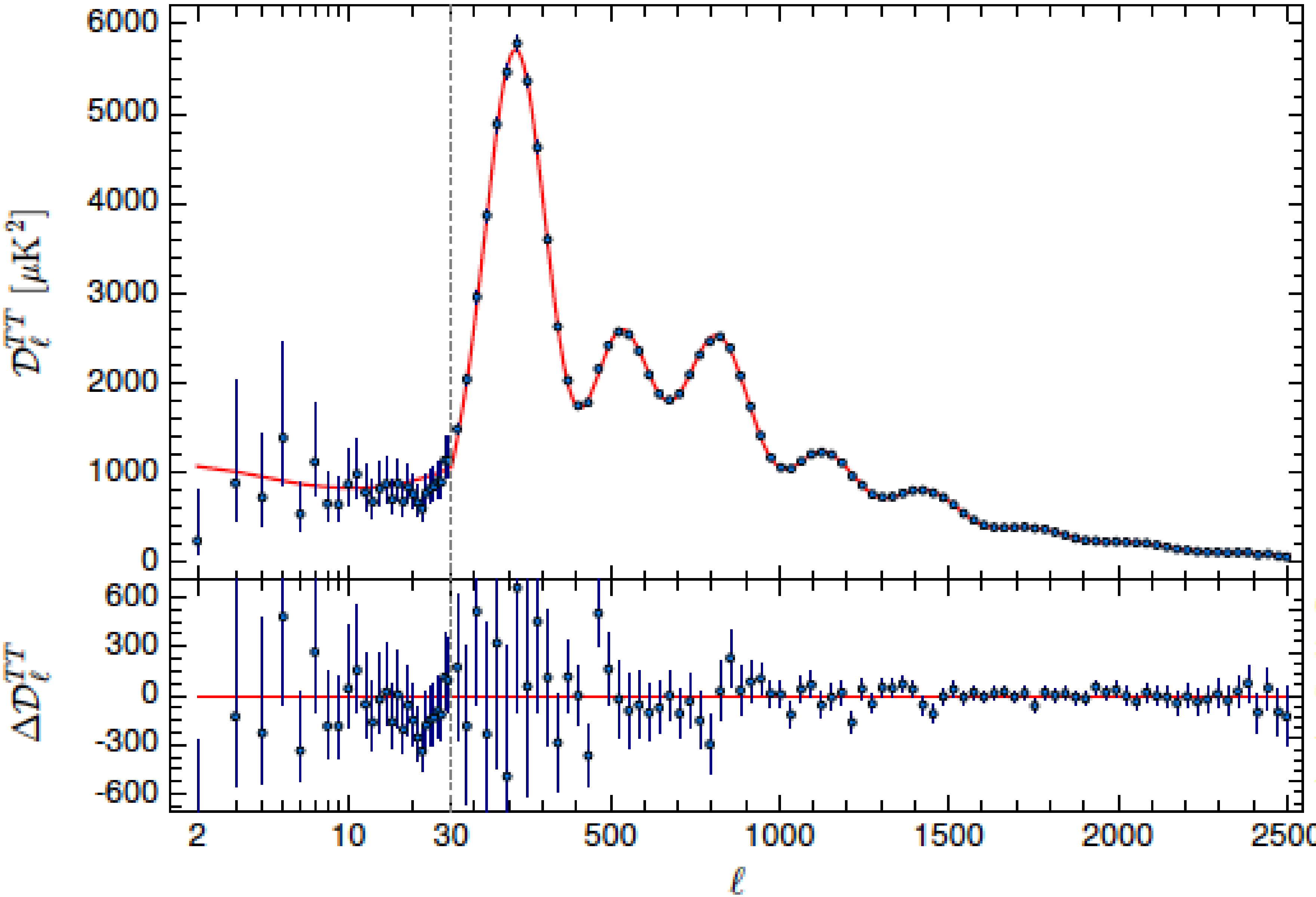
- Weak equivalence principle plus spin dictates a universal pseudoscalar (Ni 77)
- There exists at least one fundamental scalar – the Higgs boson !
- Axion monodromy – large-field inflation
- Peccei-Quinn symmetry breaking – QCD axion CDM
- Problems in small-scale structures – 10^{-22} eV scalar (maybe pseudoscalar) fuzzy CDM
- String axiverse – a plentitude of axions with a vast mass range 10^{-33} eV - 10^{-10} eV Kaloper et al.
- Extended string axiverse – axions as DE

Theoretical Predictions for CMB Power Spectra

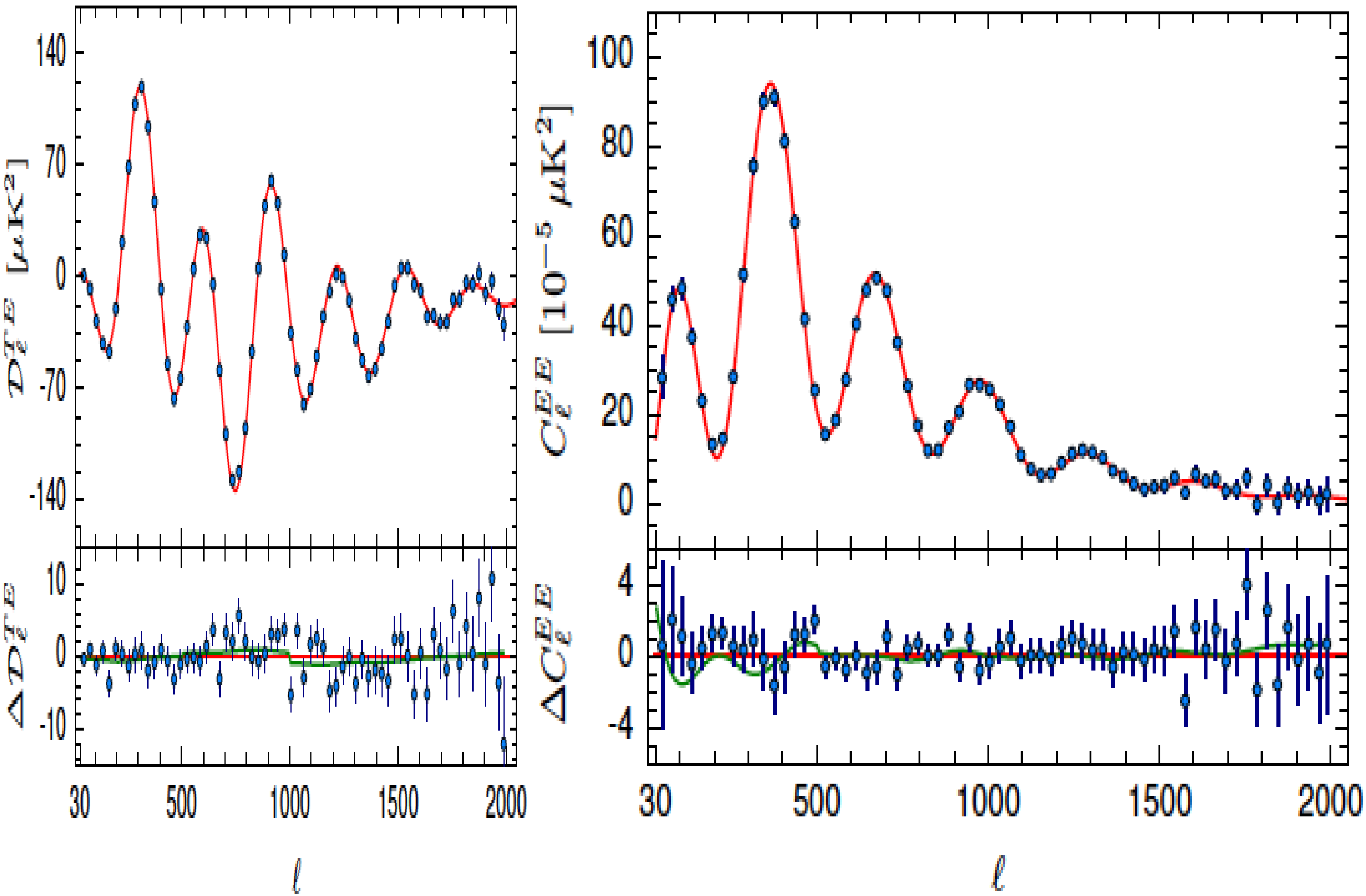
- Solving the radiative transfer equation for photons with electron scatterings
- Tracing the photons from the early ionized Universe through the last scattering surface to the present time
- Anisotropy induced by metric perturbations
- Polarization generated by photon-electron scatterings
- Power spectra dependent on the cosmic evolution governed by cosmological parameters such as matter content, density fluctuations, gravitational waves, ionization history, Hubble constant, and etc.



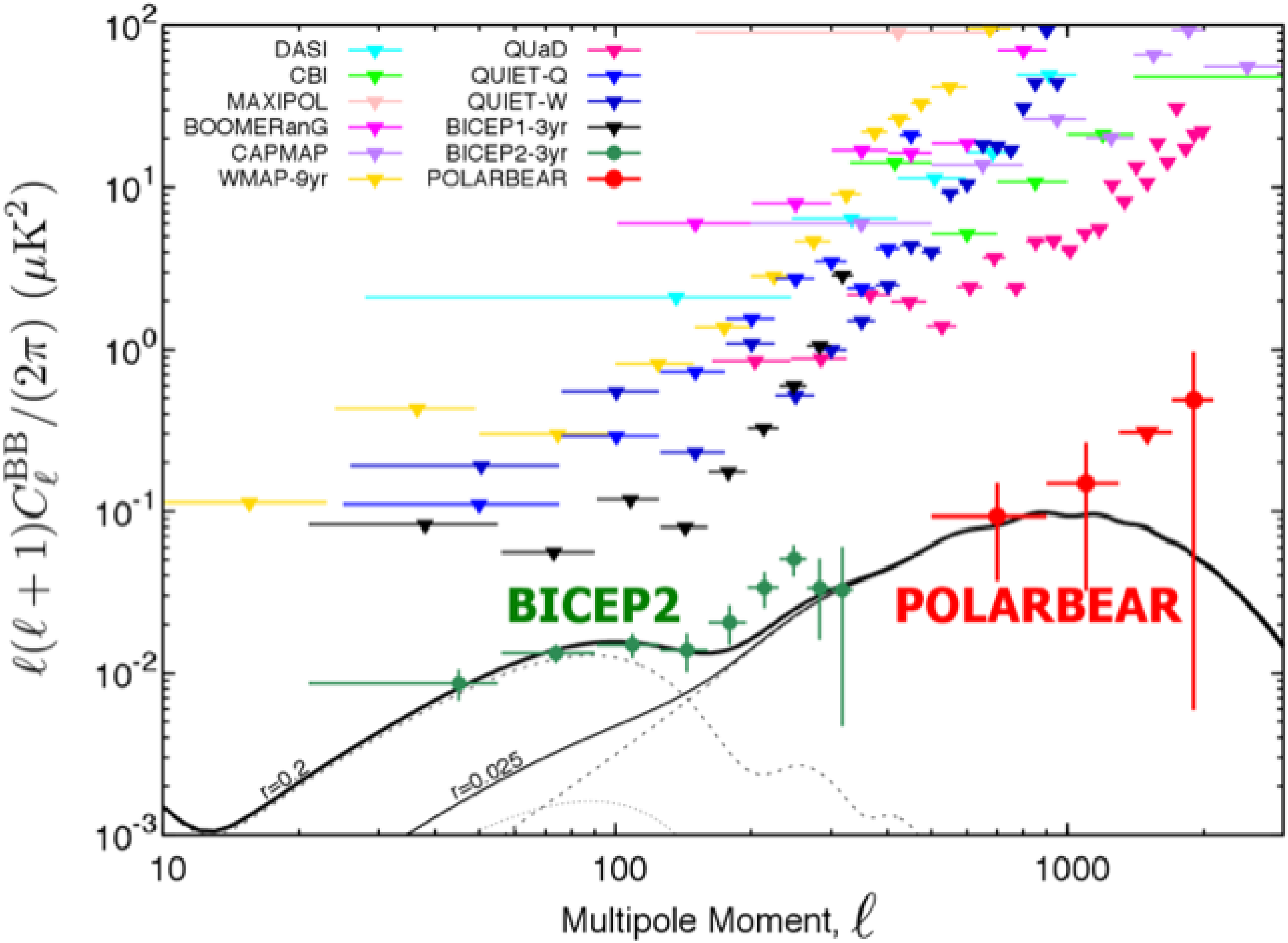
Planck CMB Anisotropy $D^{TT}_l = l(l+1)\, C^T_l$ 2015



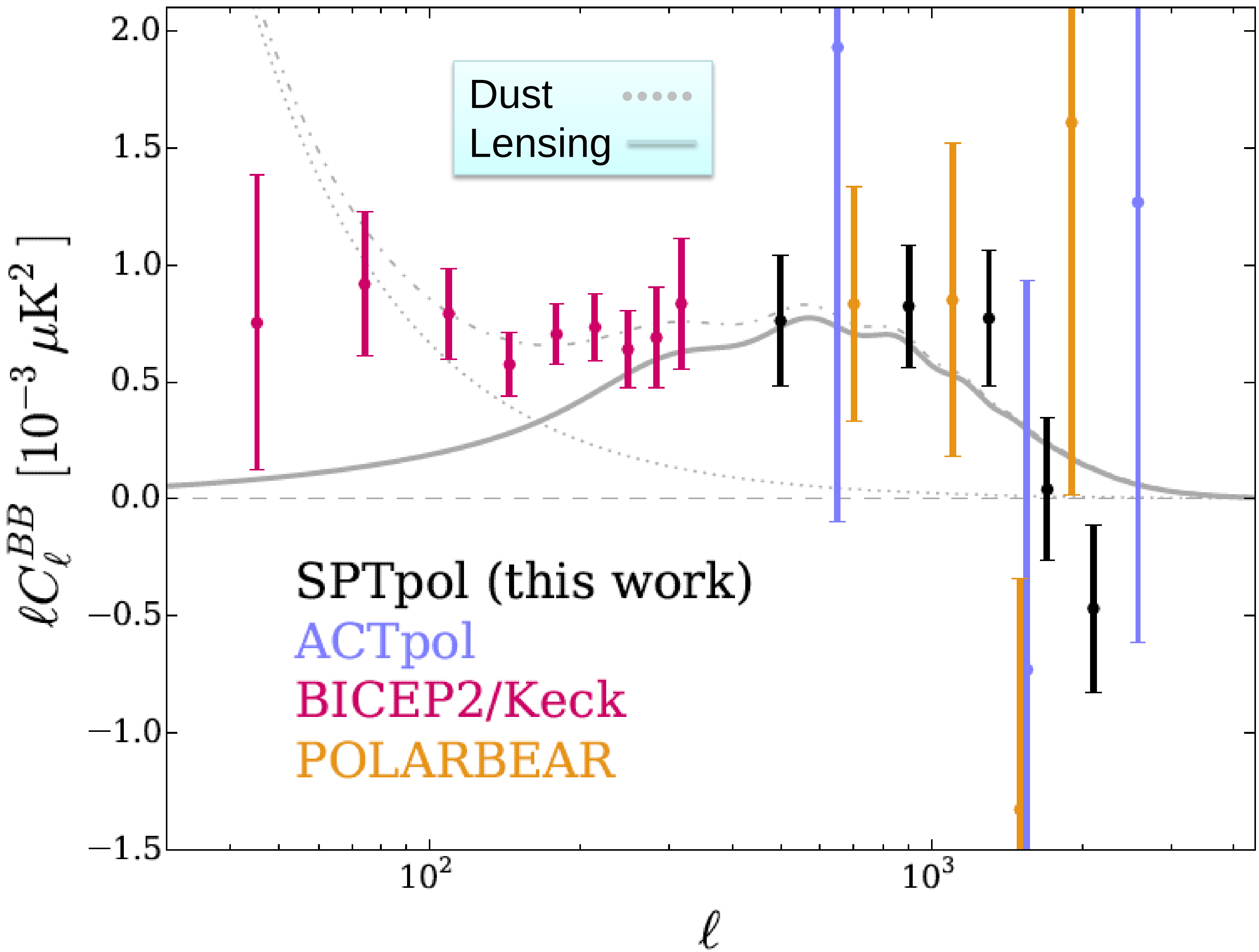
Planck CMB Polarization Power Spectra 2015



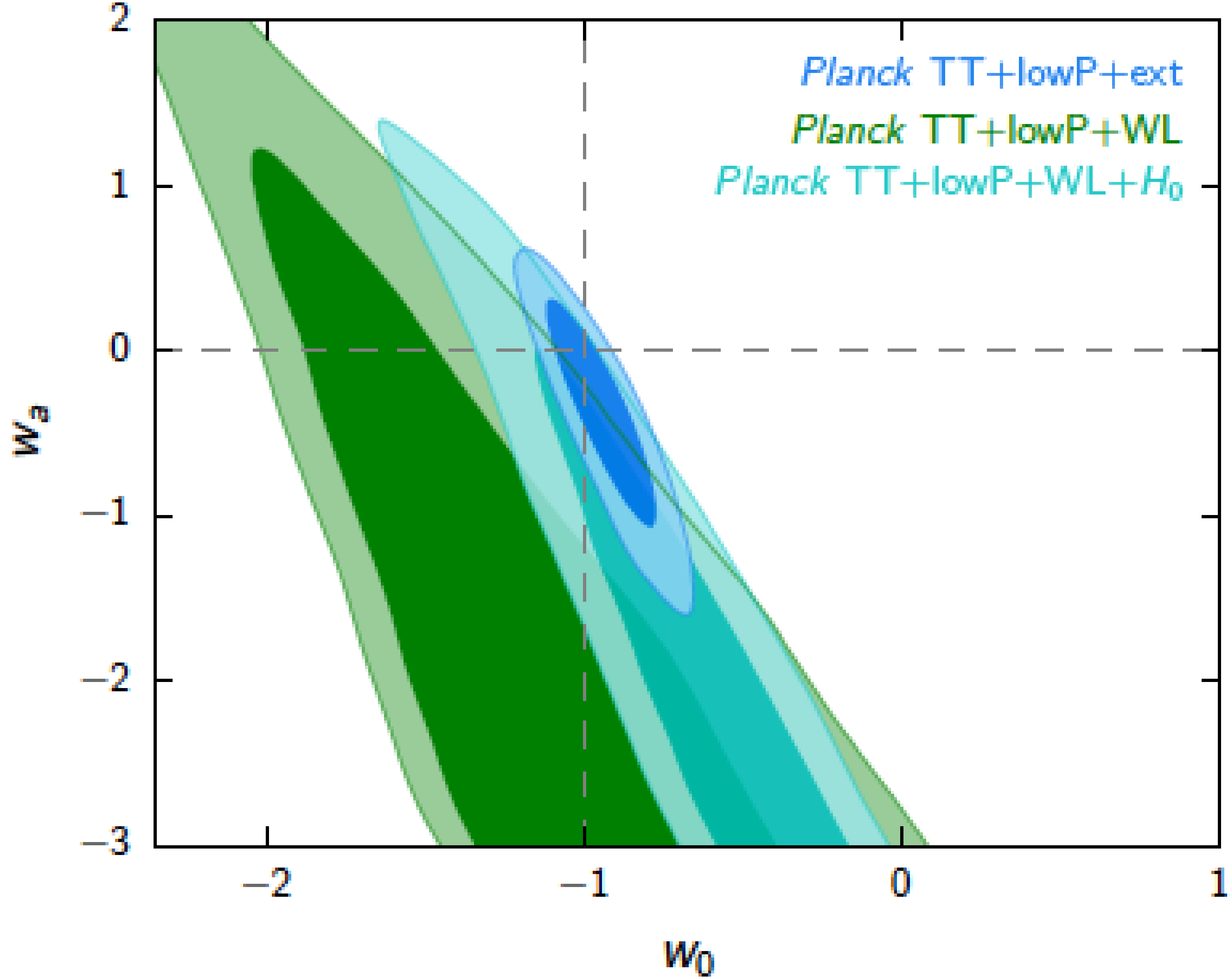
POLARBEAR+BICEP2 B-mode Detection



More B-mode detection



Time varying $w = w_0 + w_a\, z/(1+z)$



DE/DM Coupling to Electromagnetism

$$\mathcal{L}_N = -\frac{1}{4}\sqrt{-g}B_{F\tilde{F}}(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}\,, \quad \text{where} \quad \phi \equiv \frac{\Phi}{M}\,, \qquad M = M_{Pl}/\sqrt{8\pi}$$

This leads to photon dispersion relation

Carroll, Field, Jackiw 90

$$n_\pm = \varepsilon \mp \frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

$(\varepsilon, \vec{n})$ is the photon four-momentum

$\pm$ left/right handed $\quad$ η conformal time

vacuum birefringence

then, a rotational speed of polarization plane

$$\omega = \frac{1}{2}(n_+ - n_-) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

If $B=\beta\varphi$, cooling of horizontal branch stars would imply $\beta<10^7$

Radiative transfer equation

$$\dot{\Delta}_{Q\pm iU}(\vec{k},\eta) + ik\mu\Delta_{Q\pm iU}(\vec{k},\eta) = n_e\sigma_T a(\eta)\left[-\Delta_{Q\pm iU}(\vec{k},\eta)\right.$$
$$\left.\sum_m \sqrt{\frac{6\pi}{5}}\,{}_{\pm 2}Y_2^m(\hat{n})S_P^{(m)}(\vec{k},\eta)\right] \mp i2\omega\Delta_{Q\mp iU}(\vec{k},\eta),$$

$\mu = n\cdot k$,
η: conformal time
a: scale factor
n_e: e density
σ_T: Thomson cross section

Source term for polarization

$$S_P^{(m)}(\vec{k},\eta) \equiv \Delta_{T2}^{(m)}(\vec{k},\eta) + 12\sqrt{6}\Delta_{+,2}^{(m)}(\vec{k},\eta) + 12\sqrt{6}\Delta_{-,2}^{(m)}(\vec{k},\eta)$$

Cosmic rotation

$$\bar{\omega}(\eta) = -\frac{1}{2}\beta_{F\tilde{F}}\frac{d\bar{\phi}}{d\eta}.$$

$$\mathcal{L}_N = -\frac{1}{4}\sqrt{-g}B_{F\tilde{F}}(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$B_{F\tilde{F}} = \beta_{F\tilde{F}}\phi \qquad \phi \equiv \frac{\Phi}{M}$$

Rotation angle

$$\alpha(\eta) = \int_\eta^{\eta 0} d\eta'\omega(\eta')$$

Power spectra

$$C_\ell^{(E,B)} = (4\pi)^2 \frac{9}{16}\frac{(\ell+2)!}{(\ell-2)!}\int k^2 \mathrm{d}k \left[\Delta_{(E,B)}(k,\eta_0)\right]^2,$$

$$C_\ell^{EB} = (4\pi)^2 \frac{9}{16}\frac{(\ell+2)!}{(\ell-2)!}\int k^2 \mathrm{d}k \Delta_E(k,\eta_0)\Delta_B(k,\eta_0),$$

$$C_\ell^{TE} = (4\pi)^2 \sqrt{\frac{9}{16}\frac{(\ell+2)!}{(\ell-2)!}}\int k^2 \mathrm{d}k \Delta_T(k,\eta_0)\Delta_E(k,\eta_0),$$

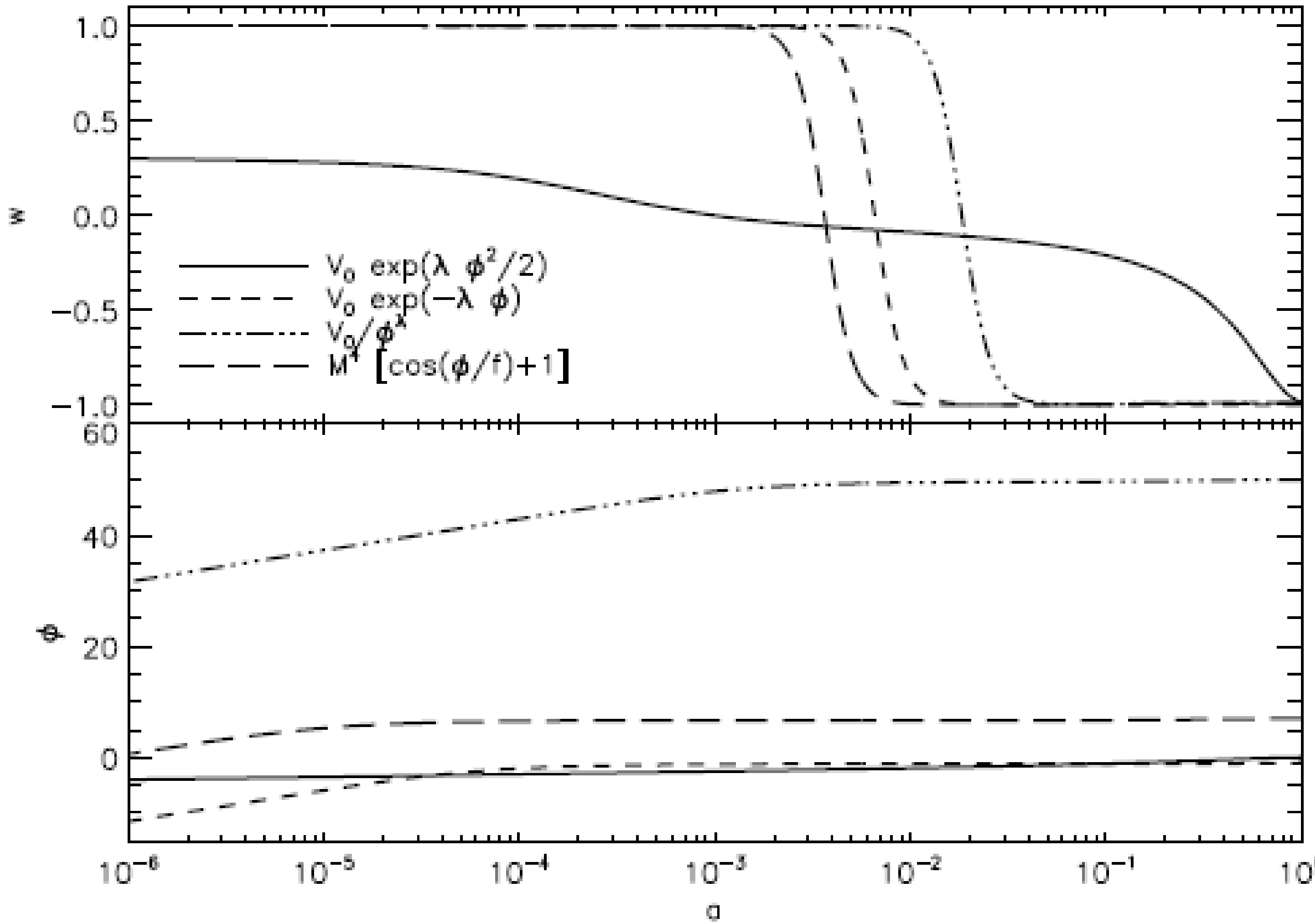
$$C_\ell^{TB} = (4\pi)^2 \sqrt{\frac{9}{16}\frac{(\ell+2)!}{(\ell-2)!}}\int k^2 \mathrm{d}k \Delta_T(k,\eta_0)\Delta_B(k,\eta_0),$$

$$\Delta_T(k,\eta_0) = \int_0^{\eta_0} \mathrm{d}\eta g(\eta) S_T(k,\eta) j_\ell(kr),$$

$$\Delta_E(k,\eta_0) + i\Delta_B(k,\eta_0) = \int_0^{\eta_0} \mathrm{d}\eta g(\eta) S_P(k,\eta)\frac{j_\ell(kr)}{(kr)^2} e^{i2\alpha(\eta)},$$

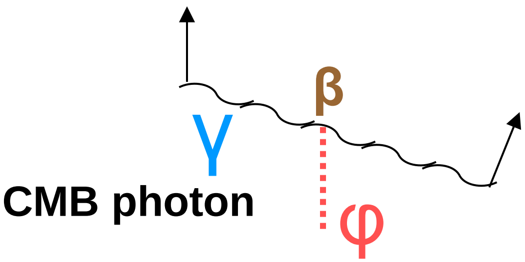
$g(\eta)$: radiative transfer function
S_T: source term for anisotropy
$S_P = S_P^{(0)}$ $\quad$ $r = \eta_0 - \eta$

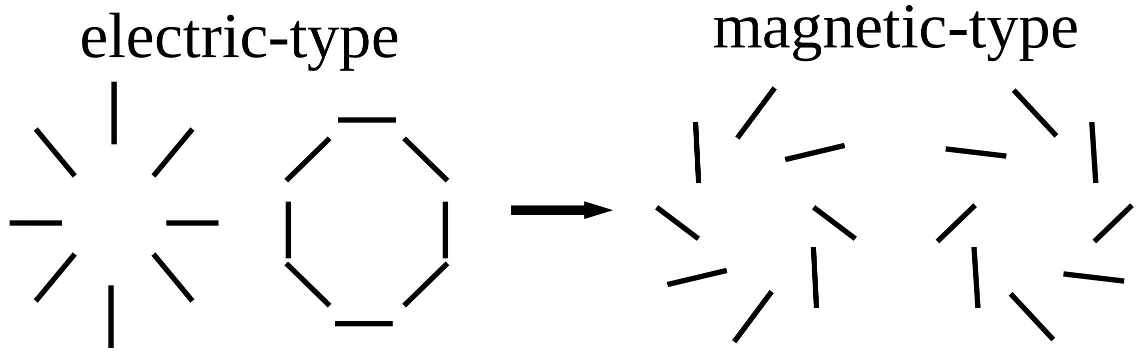
We Tried Many Scalar Dark Energy Models

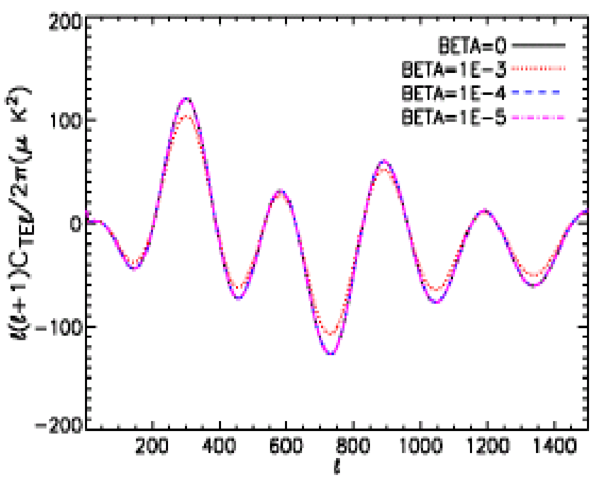


DE mean field induced vacuum birefringence – cosmic rotation of CMB polarization

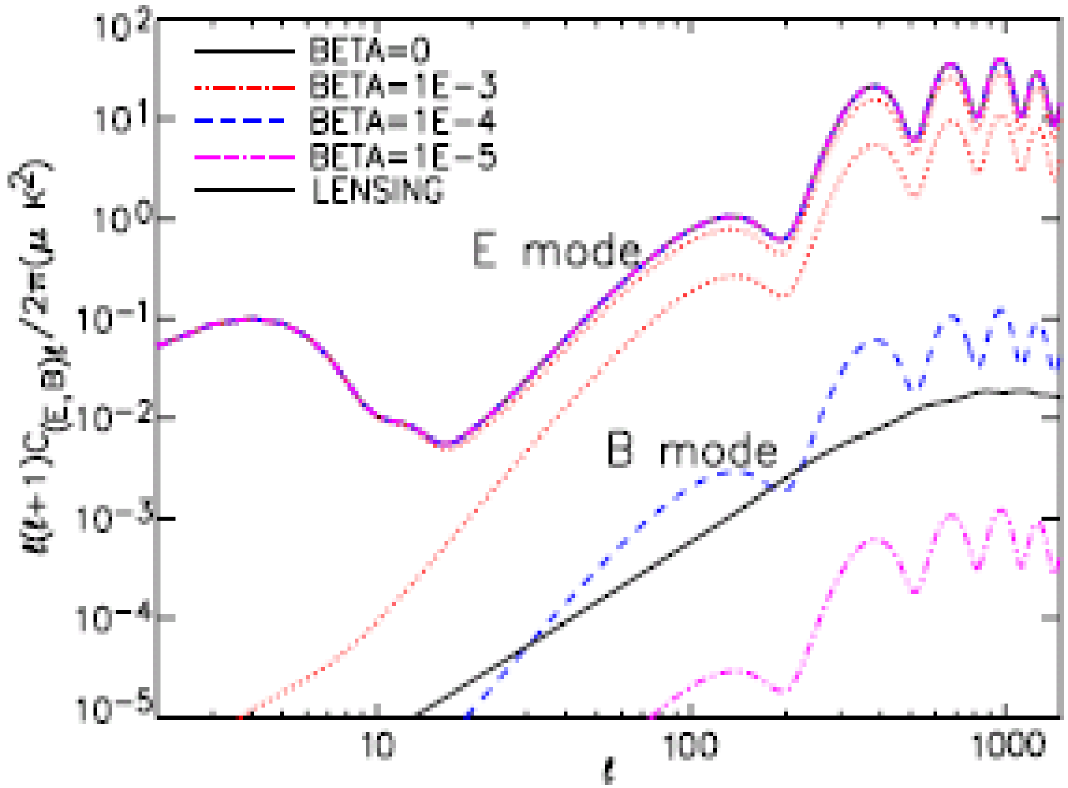
Liu,Lee,Ng 06



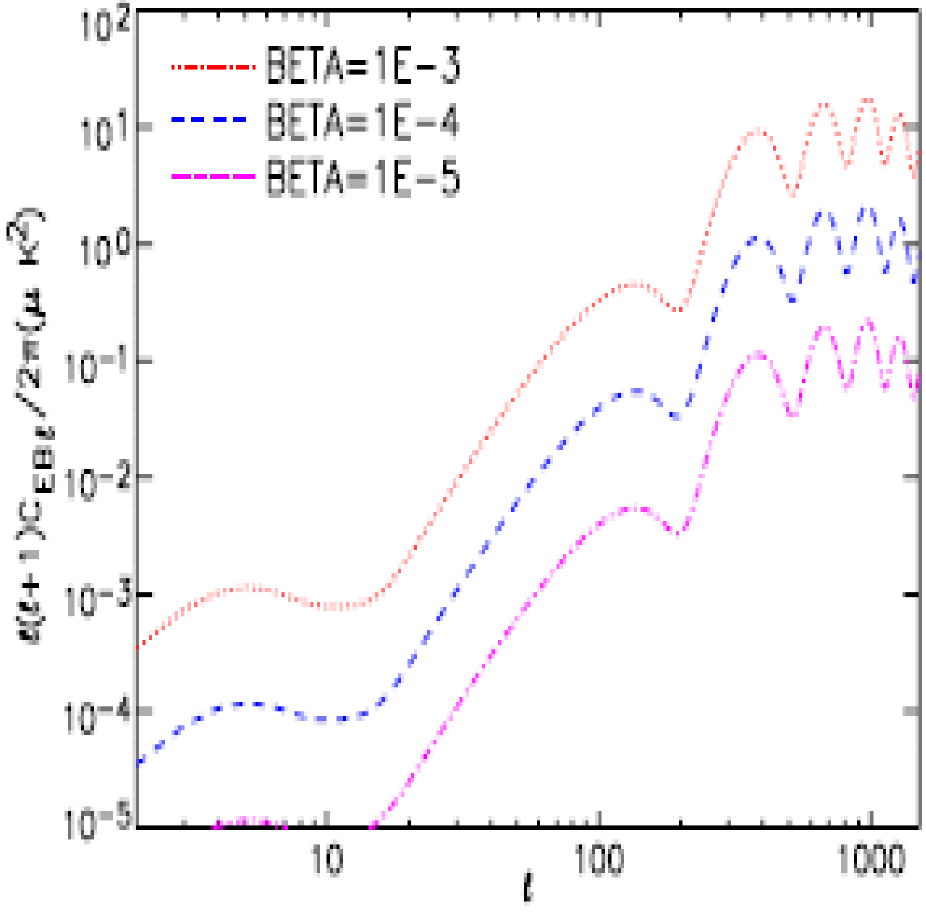


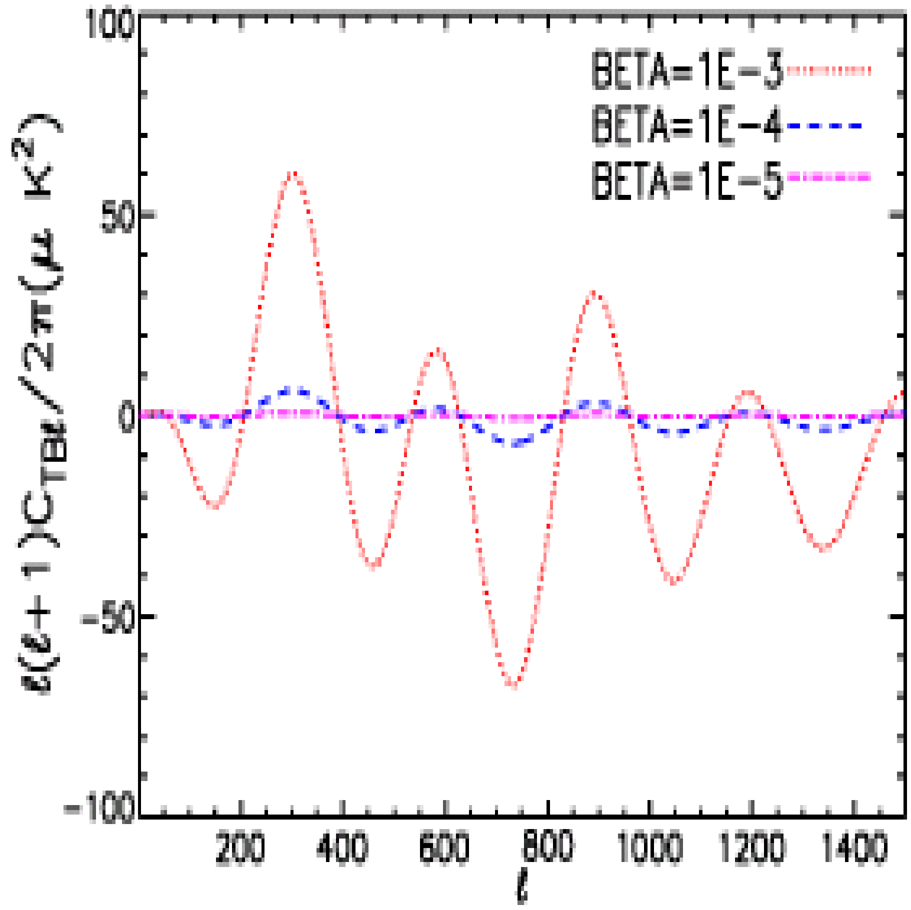


TE spectrum



Parity violating EB,TB cross power spectra – cosmic parity violation





Including Dark Energy Perturbation

Dark energy perturbation $\phi(\eta,\vec{x}) = \bar{\phi}(\eta) + \delta\phi(\eta,\vec{x})$ $\delta\phi(\eta,\vec{x}) = \frac{1}{\sqrt{(2\pi)^3}}\int \delta\phi(\vec{k}',\eta)e^{i\vec{k}'\cdot\vec{x}}d^3k'$

time and space dependent rotation

$$\omega = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\phi}\left(\frac{\partial\phi}{\partial\eta} + \vec{\nabla}\phi\cdot\hat{n}\right)$$

$$\dot{\Delta}_{Q\pm iU}(\vec{k},\eta) + ik\mu\Delta_{Q\pm iU}(\vec{k},\eta) = n_e\sigma_T a(\eta)\Big[-\Delta_{Q\pm iU}(\vec{k},\eta)\times$$

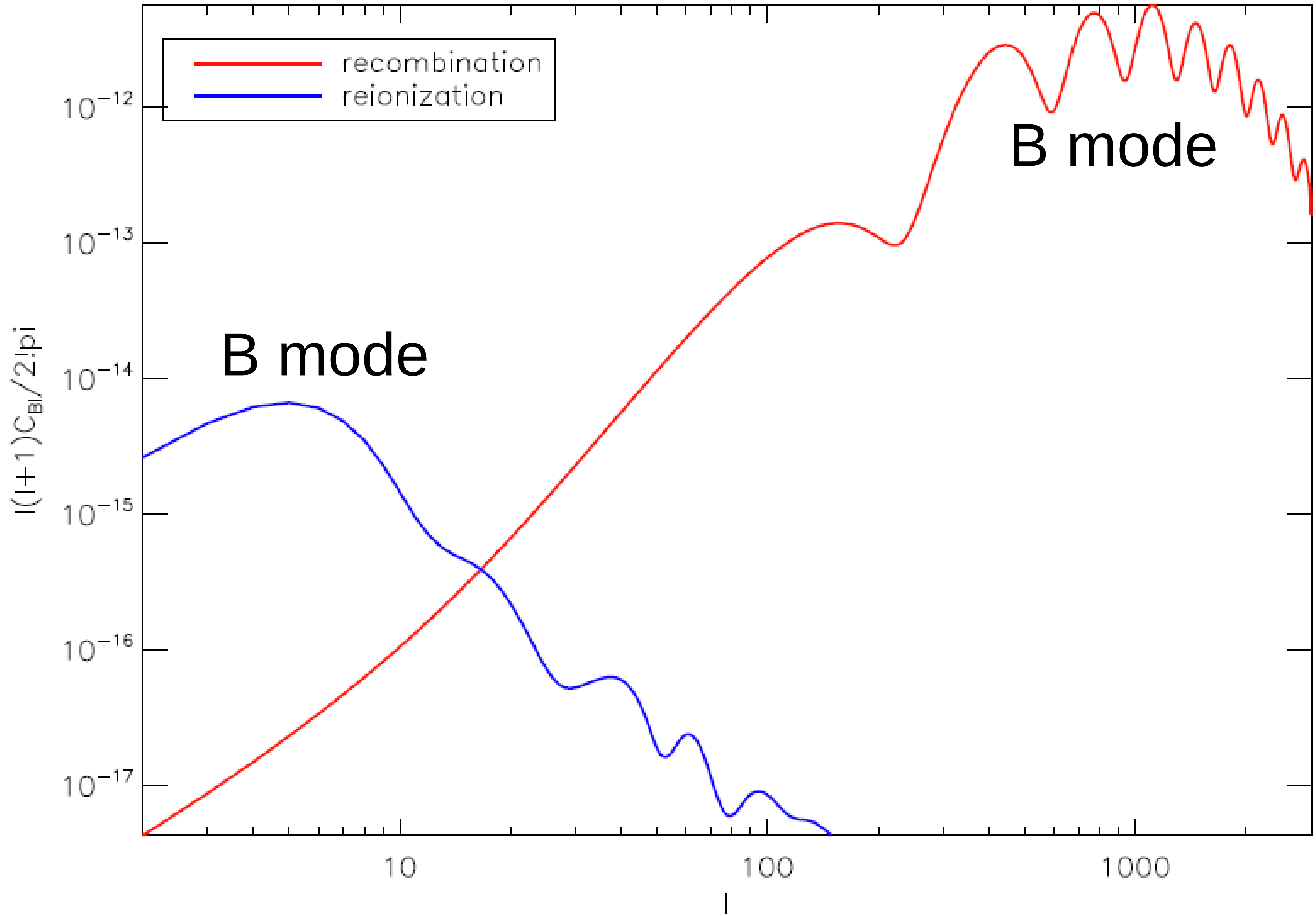
$$\sum_m\sqrt{\frac{6\pi}{5}}\,{}_{\pm2}Y_2^m(\hat{n})S_P^{(m)}(\vec{k},\eta)\Big] \mp i2\frac{1}{\sqrt{(2\pi)^3}}\int d\vec{k}'\,\tilde{\omega}(\vec{k}-\vec{k}',\eta)\Delta_{Q\pm iU}(\vec{k}',\eta)$$

$$\tilde{\omega}(\vec{k},\eta) = -\frac{1}{2}\frac{\partial B_{F\tilde{F}}}{\partial\bar{\phi}}\left[\dot{\delta\phi}_{\vec{k}}(\eta) + i\vec{k}\cdot\hat{n}\,\delta\phi_{\vec{k}}(\eta)\right]$$

- Perturbation induced polarization power spectra in general quintessence models are small
- Interestingly, in nearly ΛCDM models (no time evolution of the mean field), birefringence generates <BB> while <TB>=<EB>=0

Dark energy perturbation with w=-1 Lee,Liu,Ng 14

Birefringence generates <BB> while <TB>=<EB>=0



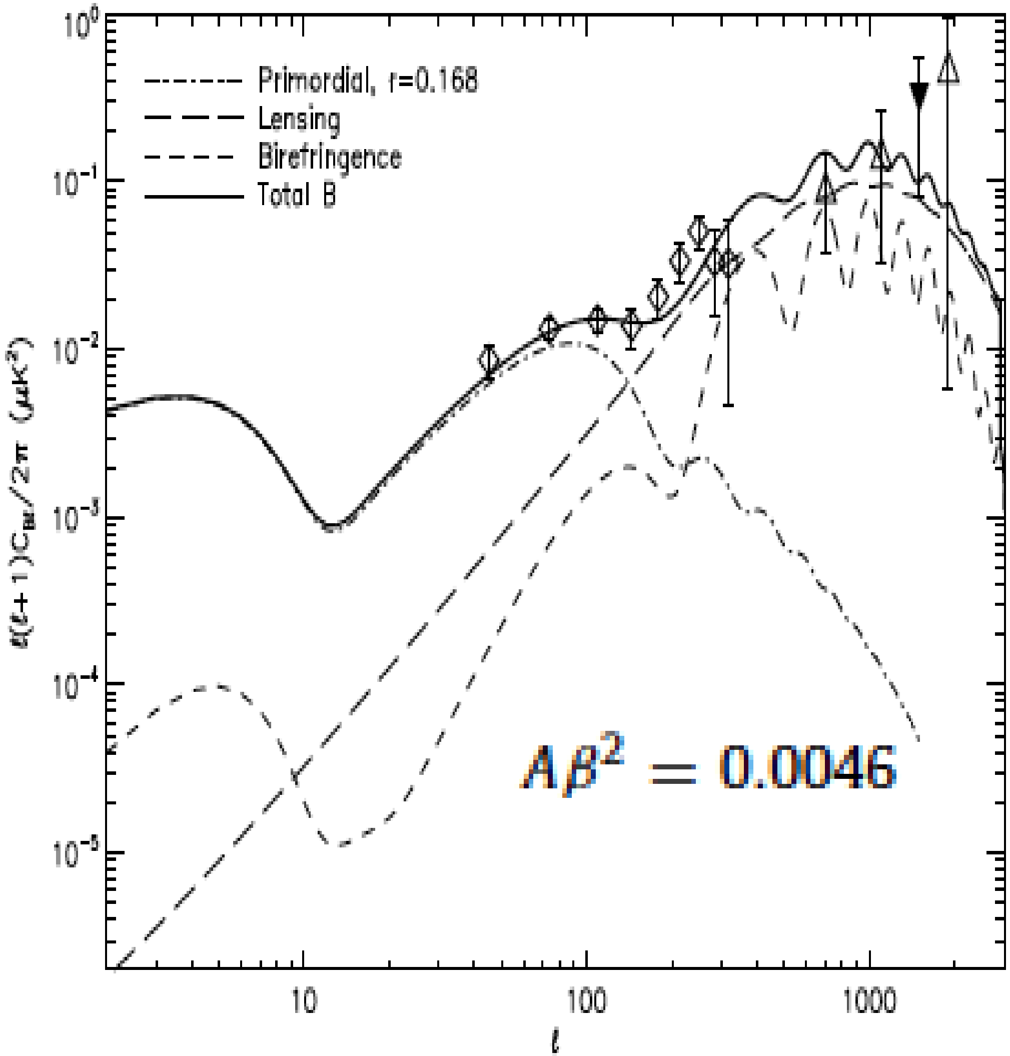
Cosmic Birefringence (CB) Fluctuations

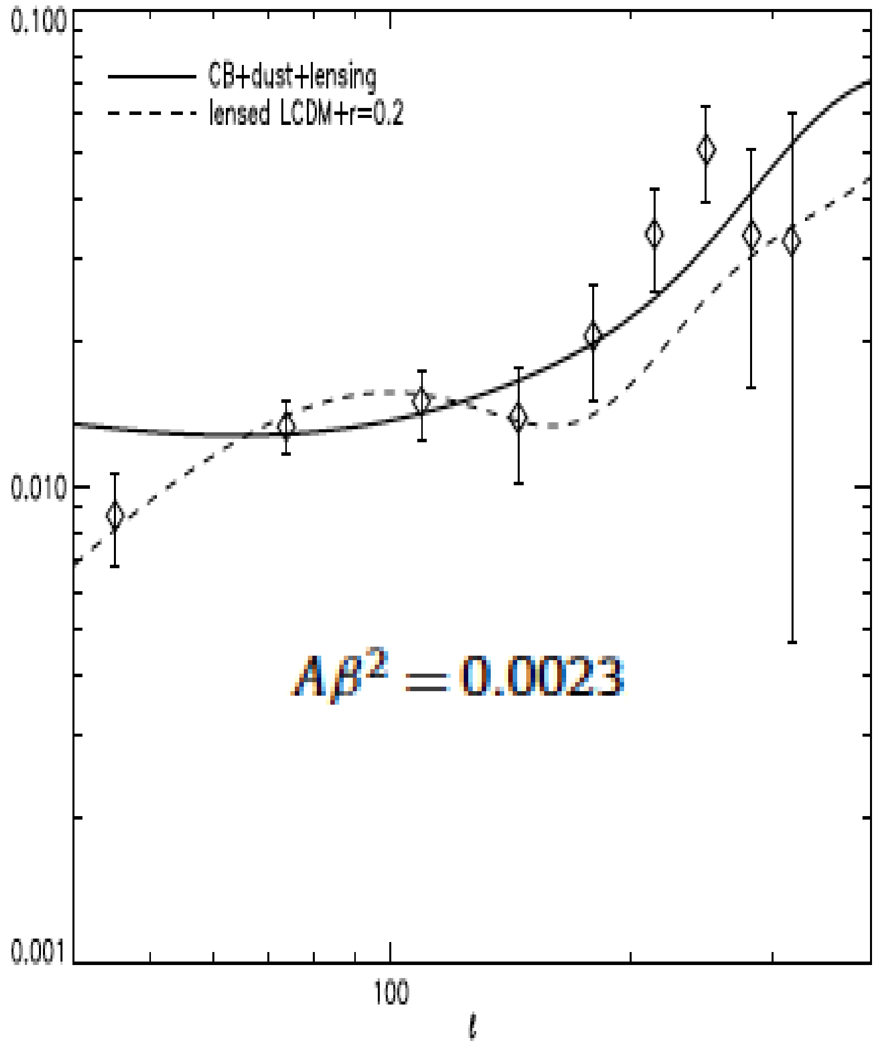
Nearly massless pseudo scalar

$$\left\langle \delta\phi_{\vec{k},i}\delta\phi_{\vec{k}',i}\right\rangle = (2\pi^2/k^3)P_{\delta\phi}(k)\,\delta(\vec{k}-\vec{k}')$$

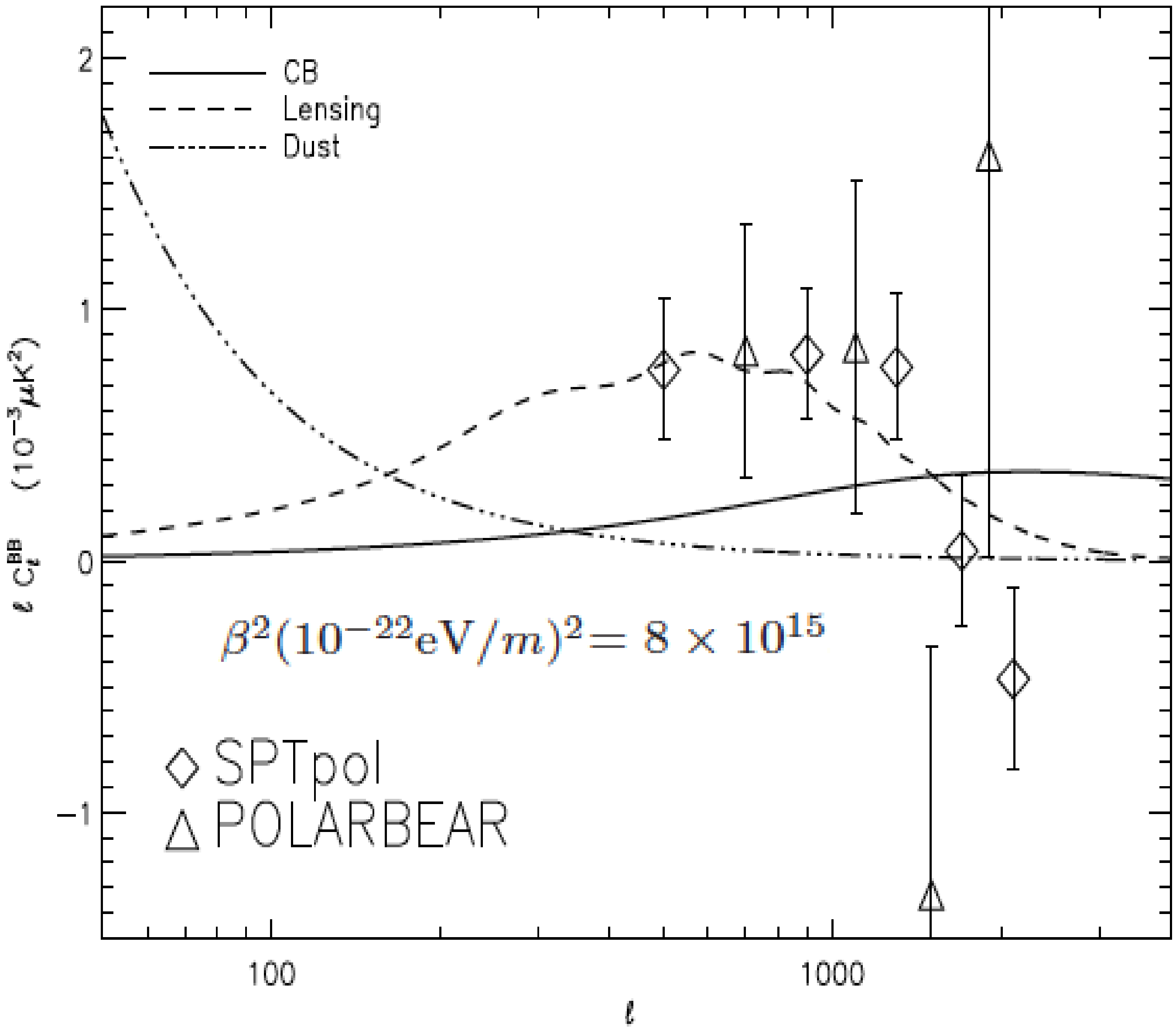
$$P_{\delta\phi}(k) = Ak^{n-1}$$

Pospelov et al 09
Lee, Liu, Ng 14





Axion ($m \sim 10^{-22}$eV) CDM curvature perturbation



$\delta\rho_\phi/\rho_\phi = \delta\rho/\rho$

$$\rho_\phi = m_\phi^2\phi^2$$

$$\frac{\delta\rho_\phi}{\rho_\phi} = 2\frac{\delta\phi}{\phi}$$

$$\frac{\delta\phi}{M} = \frac{\delta\phi}{\phi}\frac{\phi}{M}$$

$$\phi = \phi_m\left(\frac{a_m}{a}\right)^{\frac{3}{2}}$$

$$H(a_m) = m$$

Liu, Ng 16

Summary

- Using CMB B-mode polarization to search for dark energy induced vacuum birefringence
  - Mean field time evolution $\rightarrow$ <BB>, <TB>, <EB>
  - Include DE perturbation $\rightarrow$ <BB>, <TB>=<EB>=0

- Axion cold matter matter curvature perturbation $\rightarrow$ <BB>, <TB>=<EB>=0; isocurvature perturbation?

- This may confuse the searching for genuine B modes induced by gravitational lensing or primordial gravitational waves, so de-rotation is needed to remove vacuum birefringence effects Kamionkowski 09, Ng 10